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NASA Workshop on Technology for Human and Robotic Exploration and Development of Space

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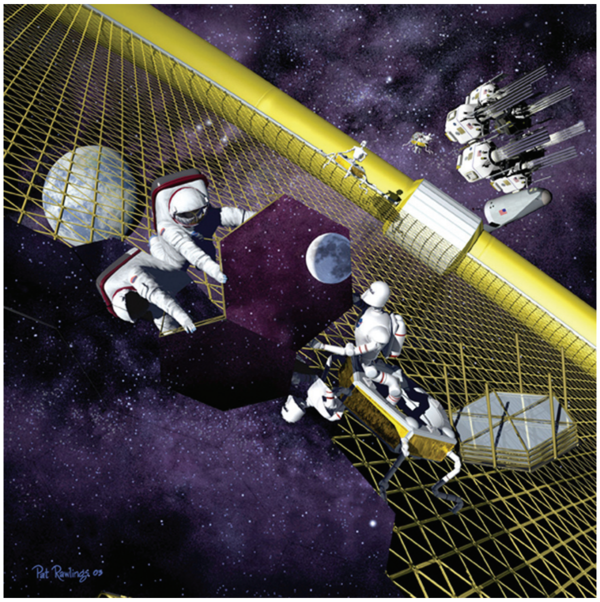
Proceedings of a workshop sponsored by the National Aeronautics and Space Administration held at NASA Headquarters, Washington, DC, August 13–15, 2002



March 2004

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The cover shows humans and robots working together to construct a future large-scale space platform. Illustrations throughout this Conference Publication are by noted space artist Pat Rawlings.

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LIST OF ACRONYMS

DRA	design reference architecture
DRM	design reference mission
ETO	Earth to orbit
EVA	extravehicular activity
FDIR	failure, detection, isolation, and recovery
HEDS	human exploration and development of space
ISRU	in situ resource utilization
ISS	*International Space Station*
ITBC	issues to be considered
IVHM	integrated vehicle health monitoring
LEO	low-Earth orbit
OTV	orbital transfer vehicle
RATWG	Revolutionary Aerospace Technology Working Group
R&D	research and development
RLV	reusable launch vehicle
R&T	research and technology
SSP	space solar power
TFD	technology flight demonstration
THREADS	technology for the human/robotic exploration and development of space
TITAN	THREADS integrated technology analysis
TRL	technology readiness level
VLSI	(table 1)
WBS	work breakdown structure
WS	work session

CONFERENCE PUBLICATION

NASA WORKSHOP ON TECHNOLOGY FOR HUMAN AND ROBOTIC EXPLORATION AND DEVELOPMENT OF SPACE

1. OVERVIEW

NASA conducted a technical workshop to identify and assess innovative architectures, revolutionary concepts, and technology needs and opportunities for a wide range of prospective future exploration and commercial development of space activities. The workshop was sponsored by NASA Headquarters and held in Washington, DC, August 13–15, 2002.

The objectives of the workshop were to review and update existing technology plans, roadmaps, and analyses that have been developed in support of human and robotic exploration and development of space, and also to identify advanced concepts and high-risk/high-leverage research and technology (R&T) in important areas. These roadmaps were collectively referred to as THREADS—technology for human/robotic exploration and development of space.

The review conducted in the workshop was extensive. Participants assessed the current strategic R&T roadmaps, reviewed relevant NASA strategic planning, and identified scenarios and concepts with applicability to a broad range of future missions. Workshop participants reviewed and analyzed designs and innovative architectures/advanced systems for the commercial development of space that also support identified exploration and scientific missions. The insight and analysis provided by workshop participants in these areas are being used to revise current technology roadmaps and development plans for breakthrough and/or key technologies.

Workshop participants discussed the importance of applying a systematic analytic approach to research and development (R&D) planning. They evaluated the modeling and analysis tools and techniques currently in use by the NASA program in technology planning for space exploration and development and suggested enhancements and improvements.

Working groups identified breakthroughs in specific technology areas that would lead to dramatic advances in space systems, space operations, science in space, and space transportation. The working groups also developed recommendations that highlighted steps on the path to meeting the ambitious technology goals they described. Key among these are the following:

- Revolutionary space systems will require attention to issues beyond the required technology investment. NASA must develop architectures to use these technologies effectively, and must consider early on the policy and regulatory issues that may be raised by these revolutionary systems.

- Achieving transformational space operations requires some reasonably clear definition of future missions and ongoing insertion of new technology into programs.

- Space science successes of the future will draw from systems and technologies that enable experiments to go at any time to any location.

- Incremental changes in current technologies are insufficient for advancement in space transportation; investments in innovative and ambitious concepts and approaches are needed.

A critical step in the process of getting space technology from the lab to orbit is conducting flight experiments and development programs. Workshop participants recommended selecting families of technology flight demonstrations (TFDs) that work well together, and then developing mission scenarios and concepts that represent these families. For this approach to be effective as a part of the overall NASA technology planning effort for human and robotic exploration and development of space, concepts and technologies must be coordinated with those being worked in other elements of the planning effort, and in particular, those technologies being modeled and assessed in the primary analytic software tool in use to support planning the THREADS integrated technology analysis (TITAN) model.

Finally, workshop participants characterized a wide range of long-term revolutionary concepts. This exercise was not designed to generate a list of future missions but to be boundary-stretching brainstorming that would enrich and inspire today's thinking.

Building on the capabilities of TITAN and drawing on the success of this workshop, the Code M Advanced Systems office, as a followup to the workshop, seeks to institute an annual review process to support technology roadmapping and to develop a robust and effective portfolio of technology investment.

Ultimately, an inclusive, ongoing process of technology planning is a vital part of NASA's planning process and of developing a shared vision of the Agency's technology future.

2. WORKSHOP PROCESS

NASA conducted a technical workshop to identify and assess innovative architectures, revolutionary concepts, and technology needs and opportunities for a wide range of prospective future exploration and commercial development of space activities. The workshop was sponsored by NASA Headquarters and held in Washington, DC, August 13–15, 2002.

2.1 Objectives and Products

Specific objectives of the workshop were to review and update existing technology plans, roadmaps, and analyses that have been developed in support of human and robotic exploration and development of space, and also to identify advanced concepts and high-risk/high-leverage R&T in important areas:

- System studies
- Revolutionary space systems
- Transformational space operations
- Revolutionary science in space
- Space transportation
- Technology demonstrations.

The review conducted in the workshop was extensive. Participants assessed the current strategic R&T roadmaps (collectively referred to as THREADS—Technology for Human/Robotic Exploration and Development of Space—at the time of the workshop), including a database (now in development) that captures information on technology metrics for a wide range of development options. They also reviewed relevant NASA strategic planning, focusing on areas where synergism between exploration and utilization/development of space was strong. Particular attention was devoted to human/robotic exploration scenarios and/or architecture and system concepts (for multiple target destinations) to identify pathways with applicability to a broad range of future missions.

The insight and analysis provided by workshop participants in these areas is being used to revise current technology roadmaps and development plans for breakthrough and/or key technologies. One of the major outputs of the workshop was updated assessments of key technology metrics; e.g., updated assessments of parametric limits and/or "boundary conditions" on surmounting human exploration challenges. Finally, workshop participants reviewed and analyzed conceptual designs and innovative architectures/advanced systems for the commercial development of space that also support identified exploration and science utilization scenarios/cases.

The results of this analysis are presented in this Conference Publication. In addition, all materials presented at the workshop have been compiled on a CD that has been distributed to select NASA recipients. This CD includes presentations prepared for the workshop and presentations generated at the workshop, as well as additional summary charts and material.

2.2 Workshop Structure

The workshop brought together experts in a range of technical disciplines from academia, Government, and industry. A full list of participants can be found in appendix A.

The structure of the workshop is depicted in figure 1. The workshop consisted of both working and plenary sessions. Participants broke into groups dedicated to different topics at the working sessions. All participants gathered at the plenary sessions to hear keynote speakers and share the results of their working session deliberations.

The workshop employed a set of tools and techniques that have been successfully used in NASA workshops on advanced concepts and technology planning over the past decade. The objectives of these tools and techniques are to generate findings that advance decision making and to maximize the value of participation in the workshop. To achieve these ends:

- Clear charges to each working group were provided in the form of a set of questions to be answered and presented to the full workshop in the plenary session, with the purpose of ensuring that working sessions generated analytic findings and recommendations.

- Session chairs and co-chairs with a clear understanding of the objectives of each working session and of the overall workshop were assigned. Chairs were responsible for ensuring that each working group completed its tasks.

- The topics covered in the workshop were explicitly linked to the THREADS work breakdown structure (WBS). Each working group was assigned topics that addressed THREADS "themes"—corresponding to specific WBS elements. The THREADS WBS is detailed in appendix B.

- Catalytic presentations, prepared prior to the workshop by each participant, were presented in working sessions to inform the group about relevant topics within that participant's expertise and to spark discussion and support analysis. Catalytic presentations for each working group are listed in tables 1 and 2 for working sessions 1 and 2, respectively.

- Rapporteurs—provided for each working group—were charged with note taking, gathering catalytic presentations, and providing support as needed to chairs, co-chairs, and participants.

- Issues to be considered (ITBC) forms provided at all sessions were used by workshop participants to document issues that they believe warrant future consideration, to document disagreements or minority viewpoints on topics addressed within the workshop, or to suggest any type of improvement to the analytic products that were the focus of the workshop, or the workshop process itself. The ITBC form asks for a statement of the issue to be considered, suggestions on potential resolution of the issue, identification of affected themes and/or technology areas, and for the participant's name and organization to facilitate followup.

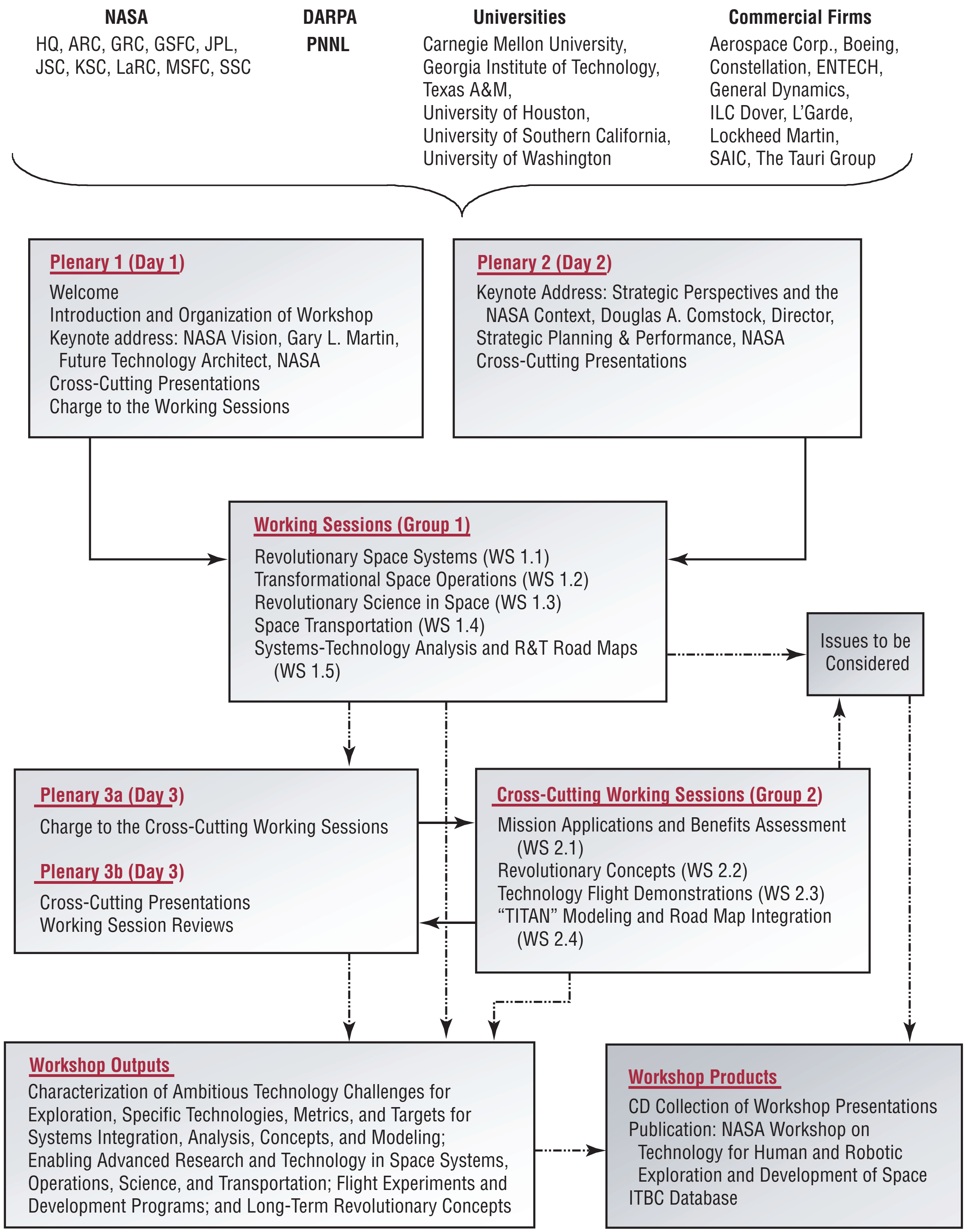

Figure 1. Structure of NASA Workshop on Technology for Human and Robotic Exploration and Development of Space.

Table 1. Catalytic presentations, working session 1.

Working Session 1.1 Revolutionary Space Systems	
Development of ISRU for Exploration	High Performance Processors and VLSI Devices for Signal Processing
Water-Based Propulsion Overview	High Productivity Computing Systems
Space Shuttle Program Status to the Space Flight Advisory Committee	Software Tools and Methodology for Reconfigurable Computing Platforms
Structural Modeling for TITAN	High Speed Networking Protocols, Network Security, and Encryption
In-Space Cryogenic Propellant Depots	Wireless Power for Exploration
Lunar Polar SSP Technology Ground and Flight Demonstration	Comet/Asteroid Protection System (CAPS): Concept Overview
Multijunction Quantum well Solar Cells for Enhanced Efficiency and Radiation Tolerance	Stretched Lens Array (SLA): A Space Solar Power (SSP) Technology for the Human and Robotic Exploration and Development of Space (THREADS)
Production of Solar Cells on the Surface of the Moon from Lunar Regolith	NASA Nuclear Systems Initiative
Information - The Key to the Future of Exploration	Micro Chemical/Thermal Systems
Catalytic Presentations, Working Session 1.2 Transformational Space Operations	
Space Robotics	Space Robotic Assembly Team Simulation (Space RATS)
History, State-of-the-Art, and Projections: EVA Systems	Robotic Orbit Modification
History, State-of-the-Art and Projections: EVA Tasks	Advanced Space Suit Architecture
Advanced Habitation Systems Technology	Lowering The Cost To Orbit Through The Use of Inflatable Structures
NASA Unique SLI Technology Development	Human-Machine Symbiosis: What are We Missing?
Satellite Servicing	
Catalytic Presentations, WS 1.3 Revolutionary Science in Space	
Adaptive Computing Systems	Breakthrough Materials and Multifunctional Structures Technologies
Power Aware Real-time Embedded Systems	NExT Design Reference Architectures
Solar System Exploration Integrated Technology Plan Guiding the Investment Strategy	Robotics Concepts to Track the Sun
(NEXT-funded) Human Operated Robotic Science Experiment: Preliminary Results	Laser-Photo-Voltaic Power Transmission Technology Demonstration to Access Shadowed Craters near the Moon's South Pole: Parts 1 and 2
Inflatable Space Structures: Affordable Space Access	
Catalytic Presentations, WS 1.4 Space Transportation	
Spaceport and Range Technologies	NASA Breakthrough Propulsion Physics Project
Nuclear Propulsion	Energy Value of Inner Solar System Missions
Future Space Transportation: A Propulsion Research Perspective	In-Space/Nuclear Systems initiative Overview
NASA Unique SLI Technology Development	Future RLV Technology
FY02 In Space Propulsion Program	Space Elevator / Tower Technologies
On-Demand Manufacturing by Layered Build Fabrication	Applications and Analysis
Addressing Technology Infusion both Horizontally & Vertically	National Aerospace Initiative: Hypersonics
Test Facilities	

Table 1. Catalytic presentations, working session 1 (Continued).

Working Session 1.1 Revolutionary Space Systems	
Catalytic Presentations, WS 1.5 Systems-Technology Analysis and R&T Roadmaps	
Systems Engineering Team Metrics Evaluation	Modeling/Analysis Flowchart
Prioritization of Advanced Space Transportation Technologies Utilizing the Abbreviated Technology, Identification, Evaluation, and Selection (ATIES) Methodology for a Reusable Launch Vehicle (RLV)	"Bifrost" – The Bridge to Space Status Report
Use of COTS and Sub-micron VLSI Processes in Space"	Technology Watch
THREADS Strategic R&T Roadmaps Update Process	Revolutionary Aerospace Systems Concepts: Program Summary
Summary of NASA Space Technology Forecast for 1980-2000, Released in 1976	

Table 2. Catalytic presentations, working session 2.

Working Session 2.1 Mission Applications and Benefits Assessment	
Government and Industry Issues for Expanding Commercial Markets Into Space	Mission Applications and Benefits Assessment
Working Session 2.2 Revolutionary Concepts	
Mini-Magnetospheric Plasma Propulsion and Radiation Shielding	Mission Applications and Benefits Assessment
Working Session 2.3 Technology Flight Demonstrations	
ISS Power Beaming Experiment and Power-Rich Technology Demonstrator	Existing Platforms for TFDs
Lunar Polar Power Missions	Technology Flight Experiment Evolution for Flying Eyeballs With Appendages
Sun-Tracking Magellan Routes for Robotic Rovers on Lunar Surface	*ISS* Power And Technology Experiment Platform, as a Replacement for the *ISS* Russian Power Tower
STS Carrier Opportunities	
Working Session 2.4 TITAN Modeling and Road Map Integration	
TITAN Model Architecture Evolution from SSM to TITAN	

2.3 Working Sessions

The two working sessions held are described in sections 2.3.1 and 2.3.2.

2.3.1 Working Session 1

Working session 1 focused on technology R&D for exploration and development of space. The breakout groups in working session 1 were as follows:

- WS 1.1—Revolutionary Space Systems. This working session addressed WBS 2.1 Self-Sufficient Space Systems and WBS 2.2 Space Utilities and Power.

- WS 1.2—Transformational Space Operations. This working session addressed WBS 2.3 Habitation and Bioastronautics and WBS 2.4 Space Assembly, Inspection, Maintenance, and Operations.

- WS 1.3—Revolutionary Science in Space. This working session addressed WBS 2.5 Exploration and Expeditions and WBS 2.7 In-Space Instruments and Sensors.

- WS 1.4—Space Transportation. This working session addressed WBS 2.6 Space Transportation, including (1) spaceport and range technologies, (2) Earth-to-orbit (ETO) transportation, (3) in-space transportation, and (4) excursion transportation.

- WS 1.5—Systems-Technology Analysis and R&T Roadmaps. This working session addressed the broad topic of systems-technology analysis with emphasis on the current (2000) family of THREADS strategic R&T roadmaps and notional updates (2002). This working session was an extended facilitated discussion intended to highlight key areas for reformulation of the roadmaps.

The charge to four of the five working groups in working session 1 was to address the following questions for the different technology areas, as follows:

- What are the ambitious technical challenges that would drive the development of revolutionary space systems?

- What are the key technology areas that are primary candidates to make these goals and objectives possible?

- What metrics must be identified and quantified to best characterize and track progress toward these ambitious goals?

- What is the current state of the art in the relevant technology areas—expressed in terms of specific metrics?

- What advances in key technology areas could be achieved—with adequate funding—that might make possible new generations of revolutionary space systems during the coming 5, 10, and 15 years (by name and by metric)?

The charge to the fifth working group, WS 1.5, differed from that of working groups WS 1.1 through WS 1.4 by focusing on the analytic process rather than on technology areas. Key questions addressed by working group WS 1.5 were as follows:

- What is the process of systems-technology analysis for THREADS?

- What are the baseline roadmaps (provided by the 2002 THREADS roadmaps)?

- What are the notional adjustments already identified?

- What significant adjustments to the THREADS roadmaps should be considered for FY 2003, including the 2000 baseline, and the notional 2002 updates?

- What are the most significant barriers to accomplishing the goals and objectives of the THREADS roadmaps?

- Other topics?

Each breakout group addressed selected elements of the THREADS WBS (app. B).

2.3.2 Work Session 2

The second working session focused on technology applications. Breakout groups in working session 2 were as follows:

- WS 2.1—Mission Applications and Benefits Assessment. A tenet of the workshop was that the broad family of technology advances represented by the THREADS roadmaps should have general applicability to many other systems, architectures, and missions. This working session reviewed this broad range of prospective mission applications and potential benefits associated with the THREADS strategic R&T roadmaps. Key topics addressed during this working session include the following:

  – What is the full range of potential areas for application of THREADS technologies—IF they were to be developed and demonstrated?

  – What are the design reference architectures (DRAs)?

  – What are the central technical strategies, design concepts, and/or technology needs embodied in future missions and applications?

  – What are some possible areas of "technology opportunity" that might be examined in the future?

  – What is the potential importance of these THREADS technologies to appropriate applications, including secondary and/or "spinoff" applications?

  – Other topics?

- WS 2.2—Revolutionary Concepts. In addition to already identified advances in technology and already "invented" innovative systems concepts that might apply these technologies, the continuing pursuit of revolutionary new systems concepts and technologies is important to eventual achievement of profound advances in space capabilities, missions, and markets. This working session considered prospective revolutionary space systems concepts and technologies. This session was a preview of the meeting of the NASA Revolutionary Aerospace Technology

Working Group (RATWG) session held following the workshop on August 16, 2002. Key questions addressed during this working session include the following:

– What truly revolutionary new systems concepts could be achieved in the timeframes of interest with technologies already validated at the technology readiness level 3 (TRL 3) critical proof of function level?

– What are the areas of science where future inventions might be anticipated and pursued?

– How might revolutionary systems concepts be applied in future architectures?

– What technologies are needed to make these systems concepts possible?

– What sort of improvements in capability (metrics) might be expected?

– Other topics?

- WS 2.3—Technology Flight Demonstrations. This working session considered cross-cutting systems issues ranging through increasingly integrated technology ground and flight demonstrations (WBS 3.1). Key questions addressed during this working session include the following:

– What are the primary options and opportunities for technology flight experiments and demonstrations during the next 5, 10, and 15 years?

– How might such technology flight missions best be accommodated (carriers, platforms, vehicles, etc.)?

– What are the opportunities and requirements for utilization of the *International Space Station* (*ISS*)?

– Other topics?

- WS 2.4—TITAN Modeling and Road Map Integration. This working session considered cross-cutting systems issues ranging from initial systems studies (WBS 1.1). Key questions addressed during this working session include the following:

– What are the prospective missions and markets that could and/or should be supported by THREADS?

– How can these be modeled to allow effective technology systems sensitivity studies to be conducted?

– How can new technologies, systems, and infrastructures (and their interrelationships) best be modeled analytically to allow the determination of the effects of one upon the other?

– What is TITAN?

– What are the available systems analysis tools and models that are relevant to the challenge of modeling THREADS systems?

2.4 Plenary Sessions

Four plenary sessions were held—one at the beginning of each day of the workshop and one at the end of the third and final day of the workshop. Plenary sessions were used for logistical and organizational information and for presentations with themes that cut across all working groups, on topics such as NASA's Vision and Strategic Plan. Plenary sessions were also the forum for working group chairs to share the analysis and findings of their groups with the full workshop audience. Plenary presentations are listed in table 3.

Table 3. Plenary session presentations.

Workshop Overview	Capability Needs for Advanced Earth Science Concepts
Strategic Perspectives and the NASA Context	Breakthrough Materials and Multifunctional Structures
NASA Vision	Information—The Key to the Future of Exploration
THREADS R&T Roadmaps Summary	

3. AMBITIOUS TECHNICAL CHALLENGES FOR SPACE EXPLORATION

Workshop results encompass four important elements of meeting ambitious technical challenges for exploration and development of space:

(1) The analytic approach is used for planning and evaluating technology programs; workshop participants provided important insights into modeling and technology roadmapping techniques that can improve decision making about technology development. Section 3.1 (Systems Integration, Analysis, Concepts, and Modeling) addresses the challenges of developing a shared frame of reference to support technology planning and of meaningfully assessing the benefits of future technology applications. It describes the tools and techniques used in the THREADS program, primarily the TITAN model and R&T roadmaps, and reports on the recommendations of workshop participants for improving them.

(2) The suite of specific technologies that are of greatest interest; workshop participants identified and characterized important technology targets and provided state-of-the-art insight into the challenges of getting from today's performance to those targets. Sections 3.2 through 3.7 summarize the analysis and recommendations of workshop participants on specific technologies. Advanced R&T is addressed in sections 3.2 through 3.5, respectively, for the following:

- Revolutionary space systems
- Transformational space operations
- Revolutionary science in space
- Space transportation.

Each section discusses the technology challenges associated with that mission area and reports on the key technologies identified by workshop participants. Key technologies are characterized in terms of the state-of-the-art performance level and future breakthrough performance levels. Each section also reports on the related recommendations of workshop participants in areas that range from technology investment strategies to appropriate analytic constructs needed for effective technology planning.

(3) The area of flight experiments and development programs is the third element of meeting ambitious technical challenges for exploration and development of space. Section 3.6 (Flight Experiments and Development Programs) discusses identification of suitable THREADS technologies for TFDs and offers strategies for viable demonstration programs.

(4) When planning for the 5- to 15-year horizon—the primary timeframe of reference for this workshop, it is also valuable to consider the longer term future. Section 3.7 (Long-Term Revolutionary Concepts) characterizes dramatic advances in space systems and technology that could be on the far horizon.*

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*This topic was further explored at a post-workshop meeting of the NASA Revolutionary Aerospace Technology Working Group session held following the workshop on August 16, 2002.

3.1 Systems Integration, Analysis, Concepts, and Modeling

3.1.1 Challenges

There is a continuing need to assure the systematic assessment of possible technologies and prospective applications and to evaluate alternative approaches to best guide technology investment decisions. Workshop participants discussed three particular challenges to this decision-making process:

(1) Establishing a shared frame of reference for decision making among stakeholders.

(2) Determining the value of alternative technology investment decisions; i.e., assessing the benefits of technology applications.

(3) Accommodating the interrelated and cross-cutting technology issues that arise among different functional areas, subsystems, and missions.

Workshop participants addressed these challenges and provided important insights into how techniques currently in use to support THREADS—modeling and technology roadmapping—can be enhanced to improve decision making about technology development for exploration and development of space.

3.1.2 Tools in Use: R&T RoadMaps and TITAN Model

THREADS employs two fundamental tools in its systems analysis and modeling activities: (1) Strategic R&T roadmaps that provide a framework for characterizing and organizing THREADS technical activities, and (2) the TITAN model. TITAN is currently in development; its function is to enable decision makers and analysts to assess complex trades among many R&T options. Both of these tools were briefed to workshop participants, and input from participants on improving the tools was sought.

3.1.2.1 R&T Roadmapping. NASA has developed a family of strategic R&T roadmaps for the advancement of THREADS. THREADS roadmaps provide a comprehensive overarching frame work for consideration of both ongoing and planned research, technology development, and demonstrations that may support the goals of ambitious future human exploration of space beyond low-Earth orbit (LEO) and the complementary commercial development of space.

The foundation for the categories and themes of the roadmaps is the THREADS WBS. The organization of the WBS was a major topic of all working groups at the THREADS workshop. Each working group reviewed the WBS elements related to the technologies being discussed and provided recommendations for additions and deletions to the WBS.

The process for roadmap updates was also a topic covered in the working group specifically devoted to THREADS R&T roadmaps. The challenges to roadmapping were discussed in depth. In general, it was noted that part of the challenge was characterizing the problem itself and then tapping the “right” people across organizations in various locations. Using modeling to aid R&T decisions was also discussed. The value of modeling is in the analysis of systems and technologies. Some of the challenges of modeling that were identified included "inventing" and analyzing new concepts and identifying and documenting technical metrics at all levels. Constraining the scope of initial objectives in model development was put forth as a strategy for THREADS, as was establishing "linkages" from engineering and projects to R&T technologies to the systems modeled. It was decided that peer reviews would be a good way to address the difficulty of model validation, generally a challenge in modeling future systems. Frequently raised concerns were verification and validation of the model.

During the roadmapping session, the need for a systematic process of R&T portfolio formulation was discussed. Participants decided the process should take into account the applications and benefits of each technology analyzed as well as the results of systems analysis. They noted that the THREADS evaluation criteria currently in use are comprehensive and that applications for evaluation should be examined over the next few months.

TFDs were also discussed during the session. The participants agreed that it is important to think about prospective applications as well as what is coming out of the R&T in the lab before finalizing choices (fig. 2). They felt that a graphical representation of a "detail-rich" THREADS hierarchy and "Advanced Concepts Studies," similar to what has been done for other NASA programs, would be useful components of the overall R&T portfolio process.

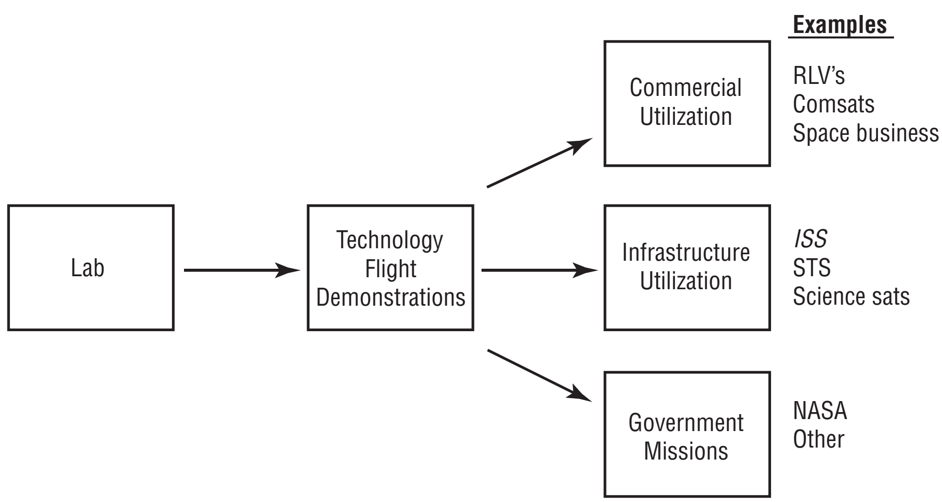

Figure 2. Issues to consider when making decisions about technology flight demonstrations.

Session participants also talked about commercial technology developed. They felt there are continuing significant issues regarding the use of—and planning for—commercial technology. It was noted that it is important to capitalize on commercially developed technologies, especially given that commercial companies have a 10:1 funding advantage over Government programs. It was also decided that the "tool kit" being developed for "Focused R&T" analysis could be very useful in exploration of the possibilities inherent in technology breakthroughs.

3.1.2.2 TITAN Modeling. The purpose of the TITAN model is to allow the assessment of diverse technology choices across a wide variety of mission architectures and system concepts. This scope involves a very complex "trade space of options," including a number of capability classes; i.e., families of major types of missions, architectures, and systems, interacting with strategic technology theme areas; i.e., self-sufficient space systems, etc., drawn from the THREADS R&T roadmaps. Figure 3 illustrates the TITAN model architecture.

The objectives of the TITAN model are to:

- Quantitatively evaluate how technology choices and/or investment decisions impact the broad spectrum of HEDS systems, missions, and architectures in terms of performance, cost, and risk.

- Provide a consistent basis of existing and projected technology information for use in these evaluations, TITAN will employ a technology "toolbox" based on the THREADS WBS, and by design, the user will be able to select and apply technology performance data from the toolbox, across the full range of modeled systems and missions.

Although TITAN will be specifically designed to accommodate human exploration and development of space (HEDS) applications, it is expected that the model will be capable of performing similar evaluations for various Earth and space science missions, as well as missions for commercial space markets. During the workshop, several missions were identified for incorporation into the TITAN model, including power beaming to Earth and a human Mars mission. It was noted that, as a minimum, TITAN would eventually address all design reference missions (DRMs), and it was suggested that these missions should be rank ordered for incorporation into TITAN.

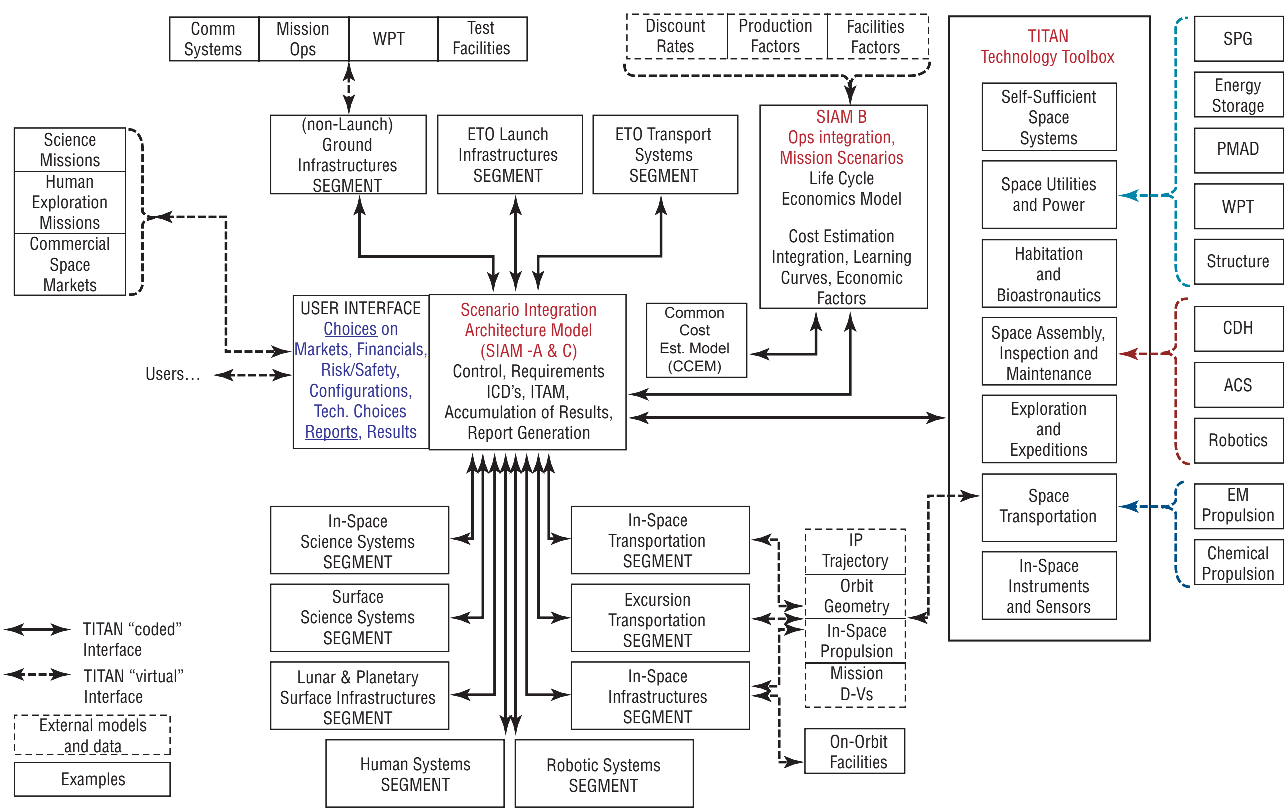

Figure 3. TITAN model architecture.

It was decided during the workshop that missions would be modeled analytically where possible. In areas where the data are too complex or the development team does not have the required expertise, the TITAN model would use outside tools that may be put into tables, curves, and other heuristics with associated boundary conditions. The use of outside models from experts generated much discussion. The participants decided that it was very important to capture detailed assumptions and mass statements from these models to understand what is going into the TITAN model. It was also noted that this would require much discussion with systems analysts who would be providing the data. To facilitate this process, the need for a detailed requirements document and user description was discussed. Concerns about casual use of such a complex model were raised as well as noting the difficulty to build in adequate protection against model misuse.

Models for incorporation in TITAN should come from various NASA Centers and NASA contractor organizations. It was noted that these models would not be fully integrated but that data and information output from these tools would be used. The TITAN development team should survey advanced concept groups to identify data interface, nomenclature, and analytical methodologies that will be feeding TITAN, such that the level of effort eventually required to trade technologies driving the DRMs is minimized. When outside models and data are used, the team should limit inputs and variations of complex element performance parameters when possible. If more depth into the element technologies is required, perform trades outside of TITAN with element/system experts, then create input "curves/algorithms" when required.

Integration of technologies, systems, and infrastructures is an important element of TITAN. The sense of the workshop was that these should be integrated in a hierarchical manner and should not be done by the concept developers but by an integration team. The integration team would be charged with modifying models by first identifying requirements for each workbook and working with concept developers to generate data and set boundaries. The integration occurs within TITAN through technology selection; e.g., SSP beaming space to Earth or space to space and propellant depot with solar arrays or rectennas. Again, the need for a requirements document was noted. This document should contain a description of data integration activities.

3.1.3 Conclusions and Recommendations

Workshop participants noted that it is important, but difficult, to appropriately involve diverse stakeholders in technology planning. At a minimum, key technology planners and strategists to be included should encompass mission and technology funding sources and advanced mission planners from all NASA enterprises, and where possible, representatives of industry. The division of timeframes used in the workshop of 5, 10, and 15 years was discussed, and it was noted that different timeframes are appropriate for different activities. For example, while 15 years may be too long a timeframe for advocacy, it is not too long for significant infrastructure development. In general, participants felt that 15 years is probably realistic for technology development, plus supporting infrastructure, plus flight planning. There was consensus that analysis of future missions should help to drive decisions about technology development in order to meet future needs in a timely manner.

Perhaps the most difficult aspect of technology planning is assessing the benefits of future technology applications. Implicitly or explicitly, this assessment is part of any choice between programs or activities.

Some presumption is being made that, relative to the resources required for each alternative, the benefits yielded by one or the other tip the scales in its favor. THREADS considers five major applications: space science, human space flight, commercial space, other Government spaces, and terrestrial applications. It was noted that the applications of different magnitudes, with different beneficiaries, are weighed the same in the THREADS decision-making process. In addition, it was noted that metric being used—"applicability"—was not sufficiently meaningful.

No consensus was reached on approaches to address these concerns. Alternatives considered included conducting beneficiary assessment to determine the distribution of benefits, and somehow incorporating those insights into decision making; evaluating each application separately, eschewing weighing; continuing to weigh all applications the same; and defining a different metric or set of metrics for each application, such as revenue, response times, operability, or safety.

Workshop participants identified several important cross-cutting technology themes—among them, intelligent operations, advanced materials, and power. Participants noted that cross-cutting themes warrant attention, especially in making R&D investment decisions; cross-cutting themes must be drawn out so decision makers understand their many impacts. This led to consideration of accommodating cross-cutting themes into technology-related planning structures, which are often stove piped by subsystem or mission area. Participants recommended modifying the WBS used for THREADS by adding an additional WBS element specifically for cross-cutting themes.

Workshop participants noted that the WBS was well thought out. Most working groups did, however, make many specific recommendations for changes to detailed levels of the THREADS WBS, clarifying categories and relationships, and adding or changing WBS elements to achieve exhaustive coverage. Several general recommendations were also made. Participants suggested that the WBS explanatory material be enhanced, providing additional information on major mission and milestone sequences and timeframes. They also suggested creating a WBS dictionary, with particular attention to clarifying and rationalizing definitions, which in some cases, reflected an inconsistent mix of functions and operations.

Workshop participants also provided insights into improving TITAN modeling. Some of their comments are more in the form of guidance to the TITAN team on issues to consider as it further develops TITAN, and others are specific recommendations.

Participants recommended that the team develop user descriptions, highlighting the fact that TITAN will not have casual users, and also develop a detailed requirements document characterizing the scope of usage. They urged full integration with DRM analysis tools. They also urged the continued involvement of modelers with detailed design-level knowledge throughout the process of model development and use.

Workshop participants noted that, where possible, real design data should be used in the TITAN development process, because "dummying up" concepts design data into TITAN would be labor intensive and could introduce errors.

Finally, participants emphasized the importance of housekeeping—TITAN maintenance, particularly maintenance of the Technology Toolbox and TITAN configuration control and size management in terms of the number of workbooks, worksheets, and links.

3.2 Advanced Research and Technology for Revolutionary Space Systems

3.2.1 Challenges

Reducing the high cost of operations and logistics for current space missions will be critical to the affordability of future ambitious space activities in LEO and beyond. This will be achieved in large part through self-sufficient space systems and improved space utilities and power.

A variety of component technologies across many disciplines must be integrated to achieve a dramatic improvement in the self-sufficiency of future space systems. While some advances, such as Autonomous Agent software, have been tested, many others have not. Technology for large-scale, modular space systems incorporating advanced wireless hardware and advanced software and technology for in-space manufacturing of operational systems spares, and the introduction of in situ resource utilization products into flight operations, are challenging areas for self-sufficiency.

Affordable, abundant, and low-mass energy systems are critical to a range of future mission options. In particular, solar power and the efficient transport of high-energy propellants are critical opportunities for the future in Earth neighborhood operations. A range of new technologies—already in the laboratory—is available for rapid maturation and application to enable a new generation of space energy applications. Lower power and lower voltage space power technology is being developed as is propellant transfer using noncryogenic fuels. However, no focused investment is being made that would enable these capabilities in the foreseeable future.

3.2.2 Technologies

The workshop team identified key technologies that addressed self-sufficiency of space systems and improved energy and power. Technologies were characterized in terms of the level of performance typically achieved today, and the target level of performance to revolutionize space systems. In addition, the team provided insight into the likely timeframe needed to achieve target performance. Details on these technologies can be found in table 4.

Table 4. Key technology areas for revolutionary space systems.

Subsystem	Technology	SOA	5 years	10 years	15 years
Wireless Power Transmission	Microwave transmitters, Magnetron	85% @ 2.45 GHz, 60% @ 5.8 GHz	50% end-to-end 5.8 GHz solid state	40% plug to laser	
	Microwave transmitters, solid state	40% @ 5.8 GHz			
	Retrodirective system	Not practically demonstrated			
	Rectenna	92% @ 2.45 GHz ~85% @ 5.8 GHz			
	Laser diode	60% plug efficiency			
	Laser conversion	60% diode to CW laser			
	PV conversion	~68% "best" GaAs at 0.83 mm			
	Direct solar-to-laser	4.8 W/m^2			
Nuclear Systems	Reactor power supply: fabrication, heat transport demo, zero power critical testing, flight qual and test	Power supply: some progress in heat transport area (liquid metal/heat pipe reactors)	Reactor materials technology	Space reactor design and test, flight test,	
	Autonomous controls: flight use over a span of years, evolution of concepts	Autonomous controls: some IVHM being pursued, some failure detection, isolation and recovery (FDIR) integrated into *ISS* C&DH	Automatic FDIR demo, autonomous controls demo	Autonomous control demo, integrated VHM/FDIR flight demo	
	Radiation tolerant electronics		Radiator materials demo, heat transport mechanisms		
	Power conversion: materials, power conversion efficiency, radiator material efficiency, deployment, demo	Power Conversion: closed system Brayton, Stirling technology research, advanced thermoelectric conductors, potential new start of K-Rankine	Power and efficiency demo	Radiator efficiency, deployment, and flight demo, NGI flight design	Advanced refractory Brayton, high power K-Rankine
	Electric propulsion: demo/flt test of high power/high ISP concepts		MPD demonstrations	High power EP flight demo	> 1Mw thruster demonstration
	Health management		IVHM demonstration	Integrated IVHM/FDIR flight demo	

Table 4. Key technology areas for revolutionary space systems (Continued).

Subsystem	Technology	SOA	5 years	10 years	15 years
Autonomous Systems Revolutionary Computing:	Ability to plan and execute simple tasks (visual photography spectrometric measurements. Collaborative capability among multiple data sources and human investigators. Preliminary integrated health monitoring and management system focusing on one vehicle system (propulsion). Preliminary nanostructures.		Integrated vehicle health management. Software engineering: human centered; autonomous systems; Vehicle health technologies that will form the basis for other revolutionary systems		
Stretched Lens Array	Lower cost ($/W)	$1000/W	$500/W	$300/W	$100/W
	Higher power/mass (W/kg)	50W/kg	200W/kg	500W/kg	1kW/kg
	Higher conversion efficiency (W/m^2)	250W/m^2	300W/m^2	400W/m^2	500W/m^2
	Compact launch volume (kW/m^3)	5kW/m^3	10kW/m^3	20kW/m^3	30kW/m^3
Space Solar Cells	PV cell conversion efficiency under AMO conditions (h) in % or W/m^2	Efficiency + 28%	Efficiency >38%	Efficiency >45%	
	Specific efficiency (SE) in W/KG	SE<160W/kg	SE>300W/kg	SE>600W/kg	
	Degradation factor (DF) in %	DF>20%	DF<10%	DF<5%	
	Cost in $/W	Cost >$400/W	Cost <$200/W	Cost <$100/W	
Intelligent Computing Systems	Radiation hardened capability of FPGA	Low	Leverage current research in GRID S/W architectures Computer architecture and operating system changes to allow use of advance H/W assist techniques Tools to facilitate use of reprogrammable hardware assist mechanisms FPGA platform that meets requirements for space systems Processing-in-memory system architecture Development of empirically-guided software development tools		
	Ability to automate the monitoring, management, maintenance, and fault correction of complex systems	Low			
	Ability of computer systems to use realtime reprogrammable hardware assists	Low			
	Ability to guarantee communication quality of service between nodes across wired and wireless networks	Low			
	Memory, and i/o bandwidth as relates to computation speed	Low and getting worse			
	Application – developer productivity (time to solution)	Extremely low			
	Development time/performance improvement	Usually high			

Workshop participants focused on integrated autonomous systems using advances in intelligent computing as key technologies for self-sufficient space systems. They addressed the development of integrated applications, system software, and system architectures that support monitoring and adaptation in response to faults and performance problems; i.e., self-healing, learning systems. They also noted that high-speed, reliably available data communication is necessary for all elements of these systems in order for them to achieve their objectives; one example is the need to communicate with self-programming systems to track their current software configuration as it changes in response to external stimuli. Improvements needed included increased reliability, speed, and flexibility.

Workshop participants discussed a range of technologies to develop highly efficient and improved space utilities. The group discussed applications of in situ resource utilization (ISRU), including producing space system fuel and water, and considered the technologies needed to support production. They discussed the system architecture for simple end-to-end water system for a space vehicle or station and the associated ISRU technology implications. Participants also discussed cryogenic fuel depots as an enhancement of space utilities to increase spacecraft life and enable new applications.

Workshop participants focused the most detailed attention on space solar and nuclear power in considering technologies to reduce energy costs and improve performance. They noted that there were advantages and disadvantages to each. For example, the relative safety of solar power adds to its appeal as a source of the massive amount of power needed for life support for human exploration missions. Large deployed systems are required, however, in order to use SSP. Nuclear power may have a size advantage and is usable without the same massive infrastructure, but has radiation-related safety and operational concerns.

Participants emphasized the fact that solar and nuclear technologies are each uniquely suitable for different missions and concluded that there is a need for a balanced research program that keeps both solar power and nuclear options open. This means investing in key technology areas that are unique to each, as well as in areas common to both. The related technologies highlighted at the workshop are detailed in table 4. Technologies related to SSP included efficiency, scalability, and materials for wireless power transmission using both microwaves and lasers and improved energy conversion from photovoltaic cells and stretched lens arrays. Technologies related to nuclear power included evolvable design, flexible use, and radiation hardening.

3.2.3 Conclusions and Recommendations

Workshop participants made three major recommendations: (1) Improve technologies in the areas identified, (2) develop architectures to use these technologies effectively—the development of TITAN as a broad, high-level process and tool that permits switching among different architectures, architectural elements, and technologies supports this recommendation, and (3) consider the policy and regulatory issues that may be raised by these revolutionary systems. Barriers to progress may be created by issues, such as safety and perceived safety for new energy sources, or by applying qualification rules for software performance that were designed for fixed code rather than continually evolving code on a remote piece of hardware. Consideration of these issues as part of the development process may help to reduce such barriers.

3.3 Advanced Research and Technology for Transformational Space Operations

3.3.1 Challenges

Operations activities involving humans and those involving large space systems are fundamental in transforming space operations; both types have broad applicability in a wide range of mission areas.

3.3.2 Technologies

Specific technology areas that will most directly affect space operations are those related to humans in space (habitation, bioastronautics, and extravehicular activity (EVA)) and those related to on-orbit space systems (assembly, maintenance, and servicing), especially large structures.

Workshop participants characterized the most important technologies in achieving transformational space operations, summarized in table 5. For each technology, the requirement for advancement is given, as well as its current level of technology readiness, using NASA's standard scale for technology maturity. In addition, the degree of development difficulty and risk associated with that technology is given, using a scale that describes technology program uncertainty in terms of degree of difficulty. Each of these measures is detailed in table 6.

Table 5. Key technology areas for transformational space operations.

Technology	Challenge/Requirement	Current Technology Maturity, Degree of Difficulty
Extra-vehicular activity (EVA)	Environmental protection EVA mobility Life support system Sensors/communications/camera Integration	TRL = 2 RD3 = 2 TRL = 3 RD3 = 2 TRL = 2 RD3 = 3 TRL = 4 RD3 = 3 TRL = 1 RD3 = 2
Advanced life support	Integrated controls Solid waste Food processing	TRL = 2 RD3 = 2 TRL = 1 RD3 = 3 TRL = 2 RD3 = 2
Long-term (> 1000 Day) mission training issues	JIT training, on-board skill training/intelligent systems	TRL = 4 RD3 = 2
Long-term psychological effects	Unknown for long-term (> 1000 days) missions	TRL = 2 RD3 = 3
Artificial gravity	Need an orbital test-bed to gain understanding and learn countermeasures	TRL = 1 RD3 = 2
Contingency operations	Example -- emergency medical ops; support of intelligent systems a must	TRL = 3 RD3 = 3
Inflatable systems	No viable ground test options (gravity); scale of on-orbit devices complicates testing and analysis	TRL = 3 RD3 = 2
Robotic experimentation in space/zero-g analog	Very little data at this time. Advancement requires significant testing	TRL = 4 to 6 RD3 = 2

Table 6. Technology development-related indices.

NASA Technology Readiness Levels (TRL)		R&D "Degree of Difficulty" (R&D3)	
Measure of technology maturity.		Measure of technology program "uncertainty."	
TRL	DESCRIPTION	R&D3	DESCRIPTION
9	Actual system "flight proven" through successful mission operations	I	Very low degree of difficulty anticipated in achieving research and development objectives for this technology; only a single, short-duration technological approach needed to be assured of a high probability of success in achieving technical objectives in later systems applications
8	Actual system completed and "flight qualified" through test and demonstration (Ground or Flight)		
7	System prototype demonstration in a space environment	II	Moderate degree of difficulty anticipated in achieving R&D objectives for this technology; a single technological approach needed; conducted early to allow an alternate approach to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications
6	System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)		
5	Component and/or breadboard validation in relevant environment	III	High degree of difficulty anticipated in achieving R&D objectives for this technology; two technological approaches needed; conducted early to allow an alternate subsystem approach to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications
4	Component and/or breadboard validation in laboratory environment		
3	Analytical and experimental critical function and/or characteristic proof-of-concept	IV	Very high degree of difficulty anticipated in achieving R&D objectives for this technology; multiple technological approaches needed; conducted early to allow an alternate system concept to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications
2	Technology concept and/or application formulated		
1	Basic principles observed and reported	V	The degree of difficulty anticipated in achieving R&D objectives for this technology is so high that a fundamental breakthrough in physics/chemistry/etc. is needed; basic research in key areas needed before feasible system concepts can be refined

For human missions, greater safety, duration, flexibility, and frequency for EVA are needed. Specific requirements include reduction of system hardware weight and volume; increased hardware reliability, durability, and operating lifetime; reduced hardware and software costs; increased human comfort; and less-restrictive work performance capability.

Advanced life support systems must reflect improvements in integrated controls, solid waste management, and food processing. Artificial gravity is a necessity for long-term human missions. Conversely, successful robotic missions will require a much better understanding of robot performance and operational challenges in space or in zero-g analog environments. There is a need for high-fidelity integrated test facilities and technology advances in artificial gravity, radiation exposure for humans, and human-machine interfaces; i.e., intelligent systems and robots.

Some of these technologies are aimed specifically at long-duration human missions; i.e., missions longer than ≈1,000 days. For example, long-duration missions will need real-time training capabilities during the mission that can only be provided by onboard intelligent systems. Perhaps more importantly, NASA needs to better understand the long-term psychological effects of long-duration missions.

For both human and robotic missions, contingency operations that can respond in a sophisticated manner to an array of situations are needed and will rely on improvements in intelligent systems.

Finally, inflatable systems will help to enable the large on-orbit structures necessary for many ambitious future missions.

3.3.3 Conclusions and Recommendations

Achieving transformational space operations requires some reasonably clear definition of future missions and ongoing insertion of new technology into programs.

Humans can play an important—sometimes essential—role in local space operations. However, it is vitally important that future space programs assure robust and reliable capabilities to support health and safety of human explorers during long-duration space mission operations as well. Moreover, such activities must also be cost effective when compared to purely robotic missions addressing similar topics.

Large space systems are required for a range of operational, commercial, and scientific mission objectives. However, current launch vehicle capacities substantially limit the size of space systems. Diverse advances in robotics, materials, computing, sensors, and other areas have been achieved in the laboratory—but not yet applied—that can rapidly transform this situation. Although low-level and/or generic research is ongoing, no focused technology investment is being made that would enable these.

3.4 Advanced Research and Technology for Revolutionary Science in Space

3.4.1 Challenges

Selecting the appropriate missions, conducting effective exploration and sample collection, and meaningfully analyzing data and samples are the fundamental challenges of space science. Revolutionary space science will require significant improvement in each of these areas. Mission selection must improve to get the most out of expensive space science experiments. Surface exploration capabilities must be significantly more robust than they are today, reliably accommodating a wide range of terrains. Sample collection must be more effective both in terms of sample selection and acquisition.

3.4.2 Technologies

Workshop participants urged a combination of standard missions and high-risk/high-payoff missions for maximum cost effectiveness. They noted that investment in site selection, using aerial mapping and composition analysis, will also be important in increasing scientific progress while reducing costs.

Space science needs the capability to efficiently and effectively select unique samples. Workshop participants emphasized that the ability to recognize the right rock to pick, gather, and transfer is key to high return on investment. Analysis of returned samples was expected to continue to be a basic element of space science. Participants found that investment in in situ laboratories will complement sample return but will not replace it. In situ laboratory capabilities were recognized as valuable, and participants felt that in situ analysis comparable to terrestrially conducted analytic capabilities was needed, and that this would be enabled by long-life, hardened instruments that can withstand fluctuations in temperature. They noted that a better understanding of microgravity effects is necessary to achieve this.

Surface exploration and sample collection were also viewed as relying on a diverse fleet of exploration robots, able to handle extreme terrains (steep, boulder, soft) and also to provide aerial photos and panoramic views.

The technology areas most critical to improved exploration and sample collection are surface robotics, navigation, high-fidelity terrain mapping, and tools; today's state of the art and future advances are characterized in table 7.

Analysis of samples and data in support of space science covers a very broad range of tools and techniques. The working group identified several areas, including analytic architectures and key decision points; in situ versus laboratory analysis; and select instruments and sensors.

Workshop participants called for a systematic processing architecture for sample preparation that guides the process from sample identification and characterization (size, color, shape) through steps that may include selecting, gathering, sectioning, slicing, breaking, cracking, polishing, and coring, and that could be applied to samples from monolithic rock to micron particle size or submicron size.

Workshop participants also noted that key decision points affect the analytic process. For example, it was noted that it is necessary to make an early decision via aerial inspection regarding when to send a robot to a sample for preliminary evaluation and/or when to bring the sample to the laboratory for detailed analysis. It was also noted that scientists generally had to make a decision regarding whether to conduct analysis for life detection and/or metrology/geology.

The technology areas highlighted by the working group as relevant to analysis were processing, operational autonomy, communication relay, and sensing/detectors, detailed in table 7.

Table 7. Key technology areas for revolutionary science in space.

Technology	Challenge	Attribute	Metric	State of the Art	Achievable in 5 Years	Achievable in 10 Years	Achievable in 15 Years
Surface Robotics	Specific power for entire robot	Speed	Km/hr	0.1	1	5	10
	Reliability and knowledge	Range	Km	10	102	103	104
	Durability	Lifetime	Months	1	5	10	100
Navigation (SLAM)	Algorithm software	Processing speed	Mips/km/hr	500	750	900	1000 more
Processing Irrespective of vehicle	Adaptive computing/ polymorphous comp	Processing speed	Mips	500	1000	2500	5000
Operational Autonomy	Task autonomy /control autonomy; planning, adaptation, learning	Activity/ command	Kbytes/ act	106	104	102	10
High Fidelity Terrain Mapping	Completeness/ resolution	Pix.sz	M	100	10	1	.1
Communication Relay	Optical direct	Bandwidth	Kbytes/sec	500	750	900	1000 more compl.
		Bandwidth periodicity	Hourly	100	Continuous		103
Tools	Sample preparation	Rock abrasion	Surface finish	Abration	Fracture	Sectioning/ sawing	Polish
	Sample collection	Sample acquisition size	Collection method	Grab scoop	Pick rock		Pick particulate
	Sample selection (uniqueness, novelty)	Classification	Classification process	Operator select			Auto designate
Sensing/ Detectors	Electromagnetic composition	Laser induced breakdown spectroscopy	Method	Conventional spectroscopy		Expanded range resolution	
	Optical structure	Resolution	Flexibility	Camera	Microscope	Vers. microscope	Electron microscope
		Feature size		10mm			10-6
	Laboratory	Laboratory in comparison to Earth lab	Type	Indivual	Non contact	Lab in a cup	Comprehensive lab

New science instruments and sensing systems for exploration, sample identification, and in situ analysis will likely become increasingly interconnected to supporting infrastructures and systems, requiring concurrent, rather than independent, decisions on technology investments in both areas. Workshop participants identified a range of advanced instruments, detectors, and sensors, including instrument operations. They highlighted the need for in situ laboratory capabilities, new biosensors, tunable sensors, automated instrument operations, and sophisticated analytic processes. See table 7 under sensors and tools for detail on specific technology advances.

Workshop participants also identified several technologies that are important in all aspects of space science. Automation and autonomy, for example, affect deployment, servicing, health diagnostics, multifunction diagnostics, cognition training, and intelligent systems. Data management was also highlighted as being key to successful operations in space science, its functions encompassing knowledge collection, processing, learning, storing, comparing, filtering, and prioritizing. The challenges of operating in a space environment were addressed. Space scientists need a better understanding of the environment and its effects for both mission and instrument design. They should also prove technology on Earth to as great an extent possible in a simulated space environment. Finally, the limitations created by energy limitations were noted, and the value of nuclear power and power beaming was discussed.

3.4.3 Conclusions and Recommendations

Future space science successes will draw from systems and technologies that enable experiments to go at any time to any location. This means that the limitations created by today's available energy supplies must be addressed. The barriers to very long-term missions—material, mechanisms, reliability, and durability technology gaps—must be removed. A mixed fleet of rovers, consisting of a few large vehicles that may be slow but have an extensive range, a few mid-sized rovers, and a swarm of insect-sized rovers, which might have either wheels or articulated legs, in the "fast, dumb, and cheap" category.

A mission architecture that could work for most destination planets would be a surveyor-based, detailed mapping of the plant followed by exploration using small, fast, long-range (in the hundreds of kilometers) insect robots with limited analytical capability to serve as scouts to identify areas of interest. It will be important that the insect scout fleet be expandable with the capability to increase sensory density if needed for confirmation of findings at a given site. The insect scouts would be followed by mid-sized, slow rovers with a suite of "insect sample collectors" like balloons, ants, wasps, worms, hoppers, cryogenic robots, swimmers, and sample collecting projectiles.

Building a robotic standard infrastructure capability will enable continuous discovery any place, any time, at reduced cost and at reasonable intervals. The feasibility of this type of infrastructure depends on a mass production mentality and a schedule of multiple missions of the same class but with a "delivery order" for every 2 to 3 years for the next 30 years. Figure 4 shows the mobile laboratory robot (Labot) derived from the robonaut concept.

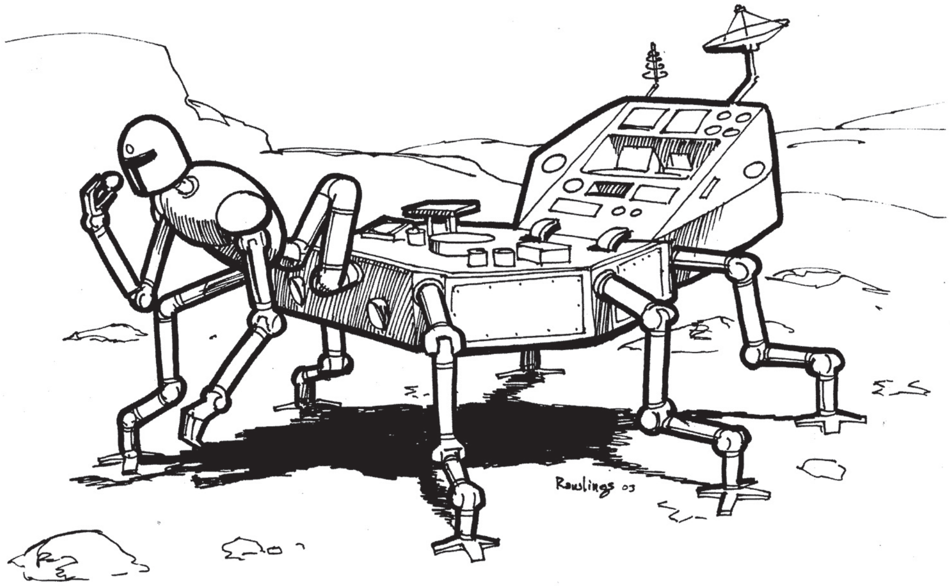

Figure 4. Mobile laboratory robot.

3.5 Advanced Research and Technology for Space Transportation

3.5.1 Challenges

Development of advanced space transportation systems requires revolutionary improvements in cost, risk, safety, and schedule. Efforts to find or produce potential breakthrough technologies are often driven by the question of whether programs are focused on humans in space or focused on robotic missions. While the notion of robotic presence as a pathway to human presence is appealing, it is not easy to implement. The requirements for robotic exploration are completely different from human exploration. Because robotic and human presence mission requirements need to be addressed with different solutions, the technology pathways associated with them should be distinctive.

Areas of synergy should be sought, but technology development programs cannot focus only on technologies that apply to both. Such an approach would eliminate important areas and limit advancement along either pathway.

3.5.2 Technologies

Workshop participants organized their characterization of specific technology advancements needed to dramatically advance space transportation into several areas reflecting different types of space transportation and infrastructure. ETO transportation emphasizes the need for reduced costs, anticipated to be enabled in part by new propulsion capabilities and new energy and power sources. In-space transportation highlights future power and propulsion requirements for access to deep space. Spaceport and range technologies focus on analytic capabilities, and smart and autonomous systems are associated with launch. Finally, the working group also noted that additional breakthroughs may be necessary in the area of excursion technologies; e.g., public space travel, although no specific technologies were identified for this area.

The workshop team identified key technologies in each of these areas, characterizing them in terms of the level of performance typically achieved today, and the target level of performance to meet the needs of advanced space transportation systems. In addition, the team provided insight into the likely timeframe needed to achieve target performance. Details on these technologies can be found in table 8. Working group participants were in general agreement regarding the technologies selected and appropriate metrics. There were two areas of disagreement: (1) Some participants raised concerns regarding bias due to a lack of structured approach in presenting data and characterizing capabilities, and (2) there was significant disagreement regarding the value of certain technologies, particularly hypersonics.

Table 8. Key technology areas for space transportation.

Target Technology	Development Time Frame (Years)
Earth-to-Orbit Technologies (ETO)	
Fission reactor power system	10
High power electric propulsion	10
Low cost ETO ($500/lb)	20
Advanced analysis (fully integrated design, development, and production)	10
HEDM (Isp>500 sec; Isp>1000 sec)	10; 15
Beamed energy	>15
Flight weight magnets (5MJ/kg)	7
In-Space Transportation	
Solar sails (100m)	10
Advanced nuclear systems (Psp>10 KW/kg)	10 to 15
High power electric propulsion	10
Advanced chemical	5
Plasma sails	15
Macro-scale nanotubes	15+
Spaceport and Range	
Probabilistic risk assessment models for launch criteria	5
‘Super Sim Spaceport’	10
Lightning launch commit criteria	<5
Mesoscale prediction	10
Seamless ground and avionics connections	15
Smart umbilicals	10
Autonomous monitoring (e.g., fluids)	5

3.5.3 Conclusions and Recommendations

The working group drew several conclusions regarding technology planning for space transportation that focused on the analytic and decision-making process. It was noted that decision support issues; e.g., how problems are characterized, what data are made available, or the process for decision making, directly shape views of what is achievable. For example, two additional decision-making challenges were identified: (1) Estimating costs and (2) disseminating and effectively using null results. In both cases, concern over perceptions that costs will be viewed as too high and affect program approval, or that null results will be regarded as negative and affect approvals, may lead to inaccuracy or suboptimal data.

There was recognition that systems analysis was a different decision-making model than what the team called the visionary approach, with both models being viewed as having merit. There was a cautionary note introduced regarding the quality of input data into technology decision making; such data is sometimes overly optimistic, because it was generated on the basis of advocacy rather than based on more objective assessment.

Finally, the working group affirmed the view that incremental changes in current technologies are insufficient for advancement in space transportation and that innovative concepts and approaches, such as those identified in this workshop, are needed.

The concept of the solar orbital transfer vehicle is shown in figure 5.

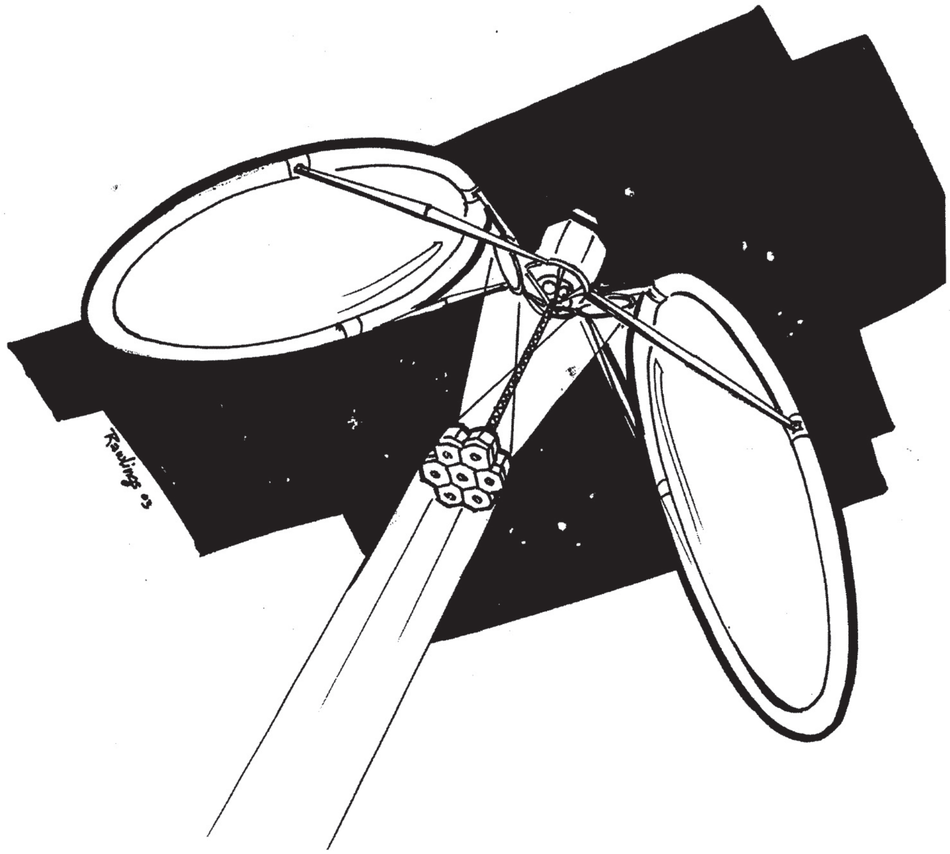

Figure 5. Solar orbital transfer vehicle concept.

3.6 Flight Experiments and Development Programs

3.6.1 Challenges

Frequently, the lack of adequate study and/or technology investments prior to making a commitment to new system development has resulted in either (1) premature rejection of new technologies critical to overall project success, or (2) significant cost overruns during development; e.g., 80 percent on average, when projects attempt to advance new technology during development. Investments in the maturation and flight validation of these technologies and systems concepts will help to enable sound future development decisions. Workshop participants considered the challenges of moving from laboratory technology R&D to TFDs—a critical step in the ultimate goal of successfully infusing new technology into NASA programs.

3.6.2 Technology Flight Demonstrations

The approach adopted by working group participants charged with considering flight experiments and development programs was to try to get as many good ideas on the table as possible. The participants raised concerns that, often, there is a tendency to prioritize and reject ideas prematurely, either because of a too narrow focus on a particular mission or mission set, or because decisions are made without consideration of the broader context. The workshop participants sought in their own discussions, and recommended as a general practice, the objective of identifying possible flight demonstrations with any and all technologies that enhance the breadth of the trade space under consideration. They viewed this approach as conducive to developing the best set of options for consideration, and felt that this encompassing approach also helped to generate excitement and interest, contributing to more and better ideas and concepts. In service of this objective, the specific flight demonstrations considered by workshop participants was broad in scope and covered a range of technologies. Discussion of these specific possible demos was used to develop process-oriented recommendations on making productive investments in TFDs. Examples of the projects discussed are in table 9.

Table 9. Example flight demos.

ISS Power Beaming Experiment and Power-Rich Technology Demonstrator
Lunar Polar Power Missions
Sun-Tracking Magellan Routes for Robotic Rovers on Lunar Surface
STS Carrier Opportunities
Existing Platforms for TFDs
Technology Flight Experiment Evolution for Flying Eyeballs With Appendages, for monitoring and maintenance
ISS Power and Technology Experiment Platform
Synergistic TFDs of *ISS* or STS upgrade technologies
Inexpensive partnered approaches for lunar surface demos
Robotic workbench on *ISS*
50m Class Aperture Deployment/Assembly Flight Demonstration
Advanced Power and Propulsion Technology Testbed on *ISS*
100-200 kWe Class Advanced Space Systems Flight Validation (LEO to GEO operations), Incorporating Advanced S/C Bus, SAMS, Self-Sufficient Operations
Secondary payloads on ELVs

3.6.3 Conclusions and Recommendations

Identifying suitable THREADS technologies for technology flight experiments requires organization of technologies into suitable flight demonstrations, taking into account whether or not the *ISS* and STS are appropriate and available platforms, and the issues and constraints of integration on these platforms. THREADS will need TFD roadmaps developed with attention to identifying demonstrations at modest cost and reflecting a balanced portfolio. THREADS will also have to consider strategies for coping with *ISS* constraints, such as limited crew time, limited EVA or robotic access to external payloads, limited power and thermal management utilities, or limited sites with orientations suitable for propulsion or Sun-tracking experiments.

TFDs should be consistent with the technologies being developed within THREADS and modeled in TITAN. They should use a deep-space 1 philosophy, providing opportunities to fly multiple high-risk/revolutionary technologies in nonmission-critical roles and providing opportunities to fly lower risk—yet still advancing the state of the art—technologies in the critical path for the TFD.

A given technology may need more than one flight demonstration; numbers and types of flight demonstrations will be determined by the technologies. To be considered for flight, a technology should have at least one issue that can only be addressed in the flight environment; some technologies can be tested on the ground to advance their TRLs.

One possibility for selecting TFDs is to establish families of technology experiments that work well together, and then to develop mission scenarios and concepts that represent these families. This approach would benefit from soliciting participation from planned upgrade programs for *ISS* or STS, to provide critical path subsystems for the TFDs, and to aid the upgrade programs in flight qualification of their systems. For this approach to be effective as a part of the overall THREADS effort, it would be important to coordinate concepts and technologies with those being worked in the rest of THREADS, and in particular, those technologies being modeled and assessed in TITAN. Figure 6 shows the external *ISS*.

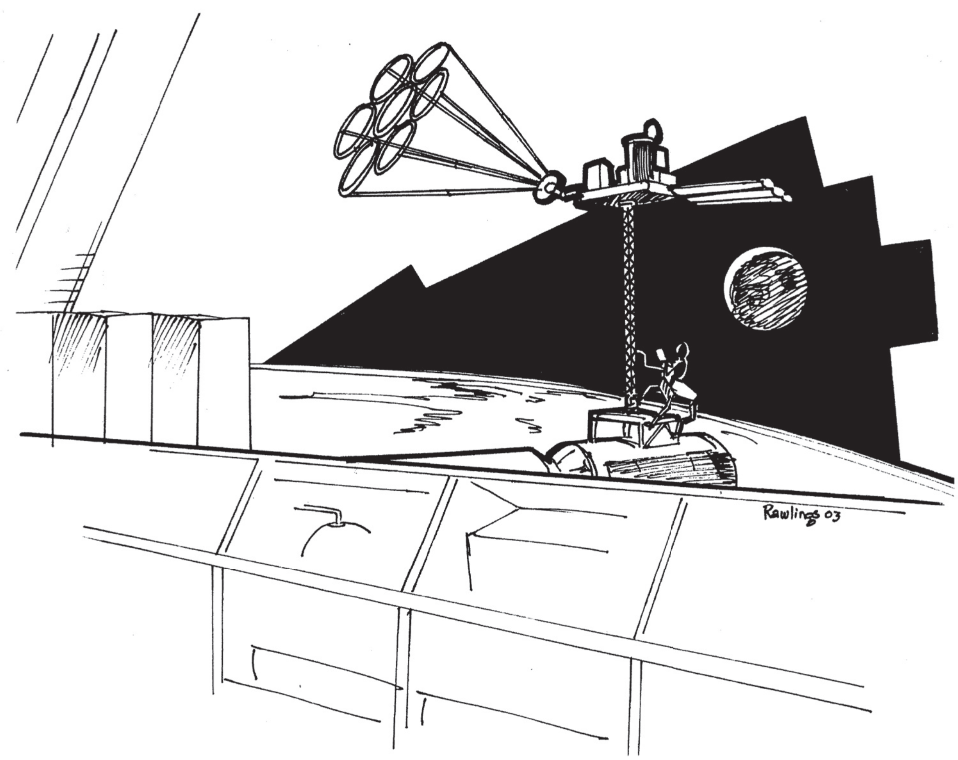

Figure 6. *ISS* external.

3.7 Long-Term Revolutionary Concepts

Finally, workshop participants characterized a wide range of long-term revolutionary concepts. This exercise was not designed to generate a list of future missions but to be boundary-stretching brainstorming that would enrich and inspire today's thinking.

Projecting technology out 25 years and beyond is a challenge. Long-term, revolutionary concepts involving dramatic technology advances may seem out of reach and unrealistic today, but some will be realized, and far exceeded.

A catalytic presentation at the workshop described a major technology study released by NASA in 1975. The study predicted turn-of-the-millennium technology advances in management of information, management of energy, and management of matter. Some of the forecasts in the study dramatically underestimated future trends. For example, the predicted information storage capability for a square meter of storage media in 2000 was what, today, we store on a drive about the size of a deck of cards. On the other hand, some forecasts hugely overestimated future trends; e.g., launch costs to LEO today are about two orders of magnitude higher than expected by the NASA study. In general, forecasts that relied only on anticipated Government funding overestimated technology advances because funding did not materialize at the expected level. Forecasts that reflected commercial and Government interest, particularly those with applicability beyond the space arena, tended to be more accurate, or to underestimate progress.

In the interests of broadening the planning community's view of the far horizon, workshop attendees characterized revolutionary concepts in space operations, space systems, space science, and future architectures. They also focus specifically on "disruptive technology" advances—technology leaps so dramatic that they would be transformative. The results are shown in table 10. The concept for the fiber optic-guided sensor (FOG-X) is shown in figure 7.

Table 10. Revolutionary concepts.

Revolutionary Space System Concepts
Space elevators (On-orbit cable connecting orbital bodies)
Mars cyclers (Spacecraft that routinely travel among Martian planetary bodies.)
Non-radioactive nuclear power (Gamma rays)
Extremely high specific energy power (Nuclear Isomers)
Carbon nanotubes for energy storage (Kinetic/magnetic energy)
Emersive presence (Virtual reality using a blanket of sensors around the planet or solar system)
Quantum entanglement (Instantaneous communication using properties of subatomic particles)
Connect neurons to silicon (For example, fighter aircraft operating from the brain waves of pilots)
Solar energy harvester (Sun for refueling, come close to other planets to discharge energy. Store it in antimatter or beam it to Moon)
Zero-point energy, vacuum energy, high Gibbs free energy molecules (Harnessing the energy of subatomic activity)
Disruptive Technology
Search for violation of equivalence principles
Weak equivalence principles (Microscopes, assess antimatter)
Local position invariance (Accurate clock on ISS)
Understand anomalous trajectories
Explore gravitoelectromagnetics
Spherical spacecraft for trajectory tracking
Antimatter
Metallic hydrogen (Core of Jupiter)
Specific impulse physics
Nano-fusion
Beamed energy
Designer humans (Photosynthesis on skin, radiation protection, genes resistant to radiations, radiodurans)

Table 10. Revolutionary concepts (Continued).

Revolutionary Science Concepts
Solar corona sample return
Planetary surveyor for non-carbon based life form (sulfur/silicon base)
Transgalactic probe
Gravitation lens observatory
Jupiter/Saturn sample return
Sun core/subsurface/atmosphere sample return
Dark matter probes outside the solar system (interstelllar)
Unstable chemical reaction spectroscopy
Extraterrestrial neutrino observatories (Neutrino change close to Sun, drill hole through the Moon)
High velocity to direction to what you want to look at (Space vehicles at the speed of light)
Gravitational wave observatories (MHz, Terra Hz)
Future Systems Architectures
Micro-nano, machine intelligence, quantum computing, quantum everything
Distributive collaborative interactive systems (Atmospheric flyers, with distributive subsystem power, computing, and sensing that work as a single structure or as a constellation. Distributive molecular spacecraft)
Impact of high-density power systems
Reconfigurable molecular machines
Modify, train virus and bacterial to relay, collect data, etc.
Biomimetics
Mold/yeast to provide nanotubes such as genes to produce new products (spider polymeric filaments)…need to be non-reproducing
Distributive machine intelligence
Convert sensing locally to long distance
High resolution Imaging from far-away
Synthetic microbes/cells

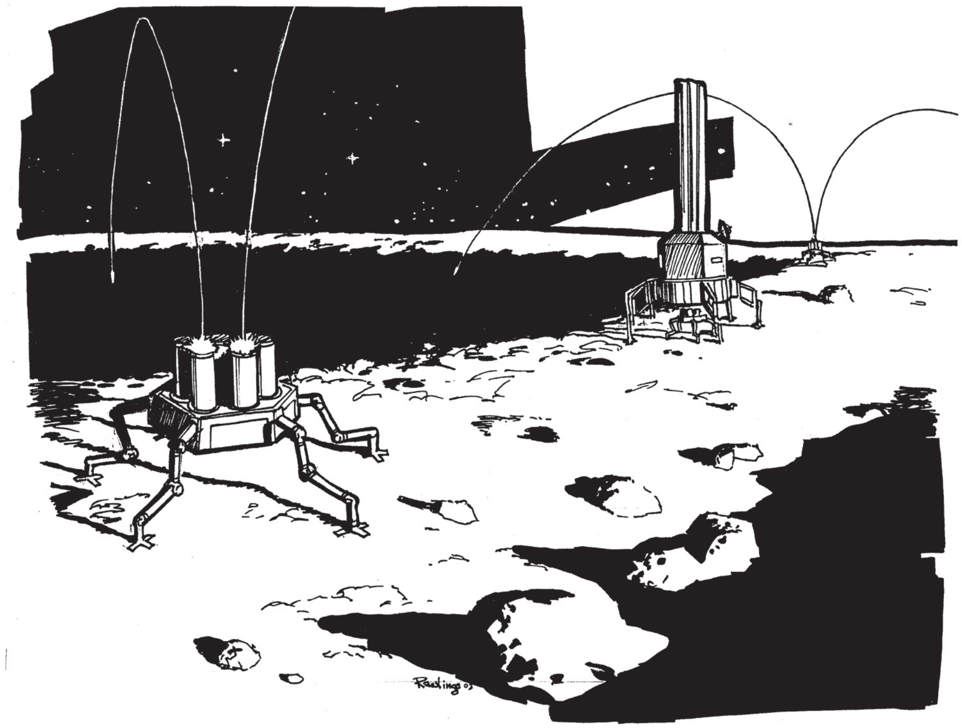

Figure 7. Fiber optic-guided sensor concept.

4. NEXT STEPS

The NASA Workshop on Technology for Human and Robotic Exploration and Development of Space was an important opportunity for NASA to review strategic roadmaps and technology portfolios and to bring in new thinking and ideas. Meetings such as the NASA Workshop on Technology for Human and Robotic Exploration and Development of Space are a valuable part of NASA's planning process. They pull together the relevant technology communities and provide a mechanism for experts to voice opinions and provide critical input into NASA's technology planning. They serve as a forum for technologists and scientists to be inspired to move into new areas or apply new analytic approaches.

The immediate next step in this process is the refinement and implementation of TITAN, the modeling tool that embodies the integrated technology analysis methodology on which this workshop was based. Building on the capabilities of TITAN and drawing on the success of this workshop, the Advanced Systems office seeks to institute an annual review process to support technology roadmapping and to develop a robust and effective portfolio of technology investment.

Ultimately, an inclusive, ongoing process of technology planning is a vital part of NASA's planning process and of developing a shared vision of the Agency's technology future.

APPENDIX A—WORKSHOP PARTICIPANTS

The attendees and presentations are listed in table 11.

Table 11. Workshop attendees and presentations.

Attendee	Affiliation	Presentation
Allen, Gale	KSC	Spaceport and Range Technologies
Baird, Scott	JSC	Development of ISRU for Exploration
Baird, Scott	JSC	Water-Based Propulsion Overview
Boland, Brian	LaRC	Systems Engineering Team Metrics Evaluation
Bushnell, Dennis	LaRC	Earth-to-Orbit Frontier Technology
Campos, Carlos	NASA HQ	
Carrington, Connie	MSFC	ISS Power Beaming Experiment And Power-Rich Technology Demonstrator
Cassady, Joe	GD Space Propulsion	Nuclear Propulsion
Cassapakis, Costa	L'Garde	Inflatable Space Structures: Affordable Space Access
Charania, A.C.	TBD	Prioritization of Advanced Space Transportation Technologies Utilizing the Abbreviated Technology, Identification, Evaluation, and Selection (ATIES) Methodology for a Reusable Launch Vehicle (RLV) [paper only]
Christensen, Carissa	The Tauri Group	Summary of NASA Space Technology Forecast for 1980-2000, Released in 1976
Cole, John	MSFC	Future Space Transportation: A Propulsion Research Perspective
Comstock, Doug	NASA HQ/B	Strategic Perspectives and the NASA Context
Connolly, John	JSC	NExT Design Reference Architectures
Culbert, Christopher	JSC	Space Robotics
Damoulakis, John	USC / Info. Sci. Inst.	Use of COTS and Sub-micron VLSI Processes in Space"
Dittemore, Ron	TBD	Space Shuttle Program Status to the Space Flight Advisory Committee
Doyle, Monica	SAIC	Structural Modeling for TITAN
Feingold, Harvey	SAIC	TITAN Model Architecture Evolution from SSM to TITAN
Fikes, John	MSFC	In-Space Cryogenic Propellant Depots
Fikes, John	MSFC	Lunar Polar SSP Technology Ground and Flight Demonstration
Fischer, Richard	NASA HQ	
Freundlich, Alexandre	University of Houston	Multijunction Quantum well Solar Cells for Enhanced Efficiency and Radiation Tolerance; Production of Solar Cells on the Surface of the Moon from Lunar Regolith
Fullerton, Richard	JSC/EMS	History, State-of-the-Art, and Projections: EVA Systems, EVA Tasks
Garbe, Greg	MSFC	FY02 In Space Propulsion Program
Gill, Paul	Boeing	On-Demand Manufacturing by Layered Build Fabrication
Glass, Brian	ARC	(NEXT-funded) Human Operated Robotic Science Experiment: Preliminary Results

Table 11. Workshop attendees and presentations (Continued).

Attendee	Affiliation	Presentation
Gross, Anthony	ARC	Information -- The Key to the Future of Exploration; High Performance Processors and VLSI Devices for Signal Processing; High Productivity Computing Systems
Hall, Ph.D., Mary	USC ISI	Software Tools and Methodology for Reconfigurable Computing Platforms
Henley, Mark	Boeing	In-Space Cryogenic Propellant Depots; Lunar Polar SSP Technology Ground and Flight Demonstration; Laser-Photo-Voltaic Power Transmission Technology Demonstration to Access Shadowed Craters near the Moon's South Pole: Parts 1 and 2
Henninger, Donald	JSC/EC	
Hoffman, Steve	SAIC	
Holladay, Jon	MSFC	STS Carrier Opportunities; Existing Platforms for TFDs; Addressing Technology Infusion Both Horizontally & Vertically
Howell, Joe	MSFC	
Johnson, Gary	MSFC	
Johnston, Alan	MSFC	
Joshi, Jitendra	NASA HQ	
Kennedy, Kriss	JSC	Advanced Habitation Systems Technology; NASA Unique SLI Technology Development
Conde, Al	JSC / HQ	NASA Unique SLI Technology Development
Leete, Stephen	GSFC	NASA Unique SLI Technology Development
Lansaw, John	SSC	Test Facilities
Lehman, Tom	USC ISI	High Speed Networking Protocols, Network Security, and Encryption
Leete, Stephen	GSFC	Satellite Servicing
Little, Frank	Texas A&M	Wireless Power for Exploration
Mankins, John C.	NASA HQ	Workshop Overview; THREADS R&T Roadmaps Summary; Mission Applications and Benefits Assessment; THREADS Strategic R&T Roadmaps Update Process
Martin, Gary	NASA HQ	NASA Vision
Marzwell, Neville I.	JPL	Solar System Exploration Integrated Technology Plan Guiding the Investment Strategy
Maynard, David	JPL	
Mazanek, Daniel	LaRC	Comet/Asteroid Protection System (CAPS): Concept Overview
Miller, Charles	Constellation	
Millis, Marc	GRC	NASA Breakthrough Propulsion Physics Project
Montgomery, Edward (Sandy)	MSFC	Energy Value of Inner Solar System Missions; Future RLV Technology; In-Space/Nuclear Systems initiative Overview
Mueller, Alyssa	Futron	
Mullins, Carie	The Tauri Group	
O'Neil, Daniel	MSFC	Space Robotic Assembly Team Simulation (Space RATS)
O'Neill, Mark	Entech, Inc	Stretched Lens Array (SLA): A Space Solar Power (SSP) Technology for the Human and Robotic Exploration and Development of Space (THREADS)
Penn, Jay	Aerospace Corp.	Modeling/Analysis Flowchart
Raju, Ivatury	LaRC	

Table 11. Workshop attendees and presentations (Continued).

Attendee	Affiliation	Presentation
Rawal, Ph.D., Suraj	Lockheed Martin	Breakthrough Materials and Multifunctional Structures Technologies
Roesler, Ph.D., Gordon	DARPA	Robotic Orbit Modification
Rohrschneider, Reuben	Geogia Tech	“Bifrost” – The Bridge to Space Status Report
Ryan, Margaret	The Boeing Company	
Schott, Brian	USC ISI	Adaptive Computing Systems
Schott, Brian	USC ISI	Power Aware Real-time Embedded Systems
Siegfried, William	Boeing	Technology Watch
Sherwood, Brent	Boeing	
Shoemaker, Ph.D., Major	DARPA	
Smitherman, David	MSFC	Government And Industry Issues For Expanding Commercial Markets Into Space; Applications and Analysis; Space Elevator / Tower Technologies
Spampinato, Phil	ILC Dover	Advanced Space Suit Architecture; Lowering The Cost To Orbit Through The Use of Inflatable Structures
Stilwell, Donald J.	JSC/EMS	Human-Machine Symbiosis: What are We Missing?
Taylor, R.	NASA HQ	NASA Nuclear Systems Initiative
Torres-Martinez, Eduardo	GSFC	Capability Needs for Advanced Earth Science Concepts
Troutman, Pat	LaRC	Revolutionary Aerospace Systems Concepts: Program Summary
Tyson, Richard	MSFC	National Aerospace Initiative: Hypersonics
Wegeng, Robert S.	PNNL	Micro Chemical/Thermal Systems
Winglee, Robert	U. of Wash.	Mini-Magnetospheric Plasma Propulsion and Radiation Shielding
Whittaker, William L. (Red)	CMU	Sun-Tracking Magellan Routes for Robotic Rovers on Lunar Surface; Technology Flight Experiment Evolution for Flying Eyeballs With Appendages; Robotics Concepts to Track the Sun
Zlobik, Renee	The Boeing Company	

APPENDIX B—THREADS WORK BREAKDOWN STRUCTURE

The THREADS roadmaps are organized around three major categories of activities and several specific themes. These categories and themes form the top tiers of the THREADS WBS shown in figure 8. The three major categories include: (1) Systems integration, analysis, concepts, and modeling, (2) enabling advanced R&T, and (3) TFDs.

Within the enabling R&T category, seven functional themes have been identified: (1) Self-sufficient space systems, (2) space utilities and power, (3) habitation and bioastronautics, (4) space assembly, maintenance, and servicing, (5) exploration and expeditions, (6) space transportation, and (7) space instruments and sensors.

The THREADS strategic R&T roadmaps, first formulated in FY 2000, will be updated each year to provide a common, living framework for prioritizing and assessing advances related to the goals of exploration and space development. The THREADS roadmaps were last updated in 2002.

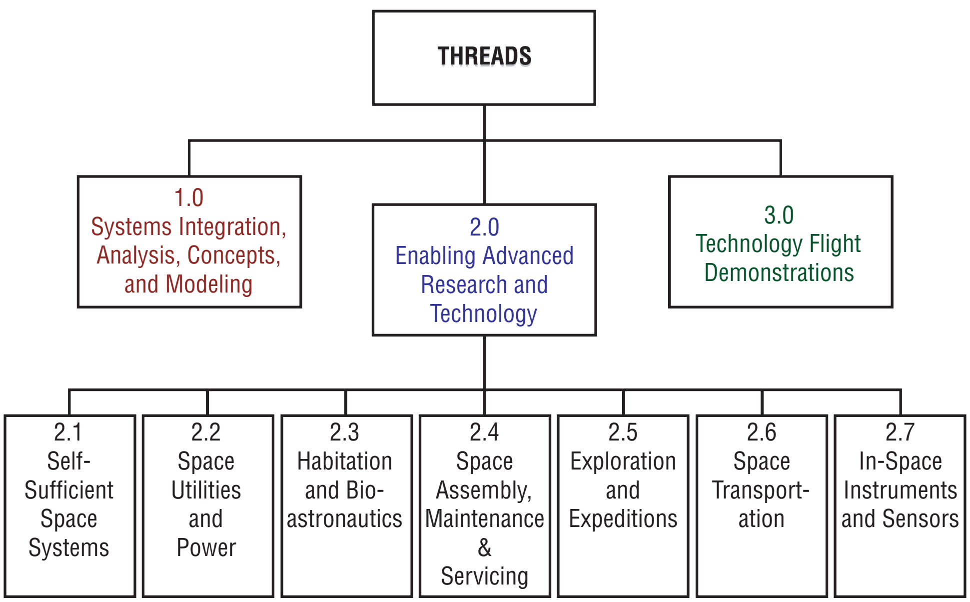

Figure 8. THREADS work breakdown structure.

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13. ABSTRACT *(Maximum 200 words)*

Continued constrained budgets and growing interests in the industrialization and development of space requires NASA to seize every opportunity for assuring the maximum return on space infrastructure investments. This workshop provided an excellent forum for reviewing, evaluating, and updating pertinent strategic planning, identifying advanced concepts and high-risk/high-leverage research and technology requirements, developing strategies and roadmaps, and establishing approaches, methodologies, modeling, and tools for facilitating the commercial development of space and supporting diverse exploration and scientific missions. Also, the workshop addressed important topic areas including revolutionary space systems requiring investments in innovative advanced technologies; achieving transformational space operations through the insertion of new technologies; revolutionary science in space through advanced systems and new technologies enabling experiments to go anytime to any location; and, innovative and ambitious concepts and approaches essential for promoting advancements in space transportation. Details concerning the workshop process, structure, and results are contained in the ensuing report.

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